UUV Teams for Deep Water Operations

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ABSTRACT

This paper presents the Unmanned Underwater Vessel (UUV) team concept, and discusses the goals of a new research effort at the Naval Research Laboratory (NRL) to develop the technologies required to implement this concept. The UUV team concept is essential to rapid and covert near-shore military operations where a communication and navigation infrastructure is not available. The UUV team concept also has the potential for lowering the cost of deep-water commercial operations and could eliminate the need for tethered vessels in some scenarios.

1. INTRODUCTION

Remote Operated Vehicles (ROVs) are used extensively for salvage operations, ocean floor surveying and numerous inspection activities that support a wide range of underwater commercial activities. In deep water (greater than 1000 ft) an ROV is the platform of choice because of the depth and endurance limitations for human divers. The key disadvantage to an ROV is the requirement for the long tether. The tether greatly inhibits the speed of the ROV, requires a ship with deck gear capable of handling this cable, and significantly restricts ship movement while deployed.

Untethered Unmanned Underwater Vehicles (UUVs) have entered the commercial market and have demonstrated the ability to perform deep-water surveys faster and cheaper than towed vessels [1-2]. With further technological advances, UUVs have the potential for supplementing and even replacing ROVs for many deep-water operations because of the cost and problems associated with the tether. One promising scenario for the near future is to use a ROV to control several UUVs in a local work area.

Table 1 compares key factors of tethered vessels to single and multiple UUVs. A tethered vessel clearly has the advantage of power and endurance, but this advantage can be lost when multiple UUVs are deployed from the same host ship. The factors of deck gear size, launch and recovery time, maneuverability and coverage rate are distinct disadvantages of tethered vessels and directly impact their cost-effectiveness.

Comparison Factors	ROV or TOW	Single UUV	Multiple UUVs
Power/endurance	+	-	+
Deck gear size	-	+	+
Launch/recovery time	-	+	+
Maneuverability	-	+	+
Coverage Rate	-	+	++
Positioning	-	-	-
Communications bandwidth	+	-	-
Intelligence	+	-	-

Table 1. Comparison of UUVs and Tethered Vessels for Deep Water Work

Accurate positioning of deep-water vessels remains a difficult and expensive issue. At present this can be accomplished with ultra-short baseline systems on GPS equipped ships that remain directly over the deployed vessels [1]. A tether offers a distinct advantage in the areas of communications and intelligence since it provides high-bandwidth instantaneous communications and allows human intelligence to be in the loop for vehicle operation. The communications, intelligence and multi-vessel navigation capabilities required for deploying multiple UUVs are at present R&D issues.

In the next section the UUV team concept is presented for near-shore military operations where speed of coverage and covertness are critical issues. In Section 3, this idea is extended to concepts that would be viable for deep-water commercial applications. Both of these concepts share the attribute that an existing positioning and communication infrastructure does not exist; in both cases, this infrastructure needs to accompany the vessels and be deployed easily, quickly and with minimal additional cost.
Finally, section 4 presents the goals of a new research effort at NRL that will explore the interrelated areas of communications, navigation and intelligence for UUVs. The goal of this research is to develop

techniques that will enable the use of multiple low-cost vessels that are slaved to a high-cost 'host' vessel for accurate positioning and for communications.

2. UUV TASK FORCE CONCEPT FOR MILITARY OPERATIONS

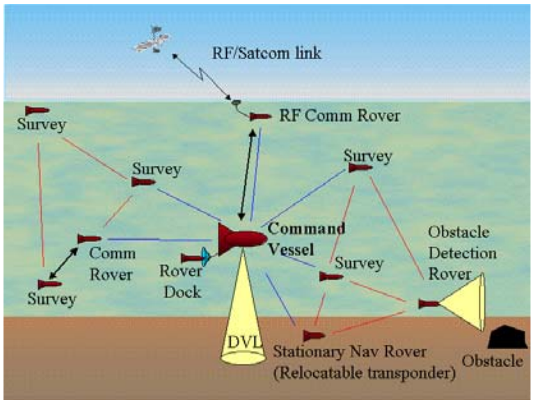

Figure 1. A UUV task force concept for a notional oceanographic mission. The blue lines indicate range/bearing positioning links and the red links are range only positioning links. The black lines indicate communication links.

A. TASK FORCE CONCEPT

Figure 1 illustrates a notional concept for a UUV task force that could be used to conduct an oceanographic survey. Data of interest in such an operation would include bathymetry, acoustic imagery, wave characterization, sediment type, water salinity and temperature, currents, bioluminescence, water clarity, etc.

An important aspect to note is that a survey of this sort could cover large areas (many square miles) and need to be executed in a fairly short period (a few days). Due to the characteristics of the vessels and the sensors involved, high vessel speeds cannot typically be used. Consequently, a large number of vessels are required to accomplish the mission as is shown in the figure.

As with most operations employing a large number of assets, it is not economically feasible or desirable for all vessels to have capabilities of the same type and grade. Bathymetry and acoustic imagery for example, require a vessel that can cruise smoothly at fairly low speeds. Sound velocity profiles (salinity and temperature) need a vessel that is good at performing vertical excursions. Obstacle sensors are not necessarily required for every vessel; a maximum safe depth can be set based on a priori knowledge of the operation area and a few vessels equipped with look-ahead sonar can be deployed ahead of the task force to ensure safe navigation for all vessels. Close inspection of an object of interest would require a vessel with a hover capability and a high-resolution imaging system.

For this scenario, no existing infrastructure exists for vessel positioning and communications and it would not be desirable or economic to put a fixed system into place for a one-time operation. Consequently, the vessels themselves must provide the functionality required. As with vehicle and sensor capabilities, positioning and communication requirements will necessarily vary from vessel to vessel. The remainder of this section introduces notional schemes that could provide the necessary capabilities without the use of support ships or the deployment of fixed systems such as a long-baseline (LBL) transponder system or an acoustic communications network.

B. COMMUNICATIONS

A command link to the outside world is required for both military and commercial operations for status monitoring and for task force redirection. Instead of equipping every vessel with this capability, this requirement can be served by a vessel that provides a radio/acoustic communications interface to the task force's Command Vessel (CV) as shown in the figure. It is advantageous to put the RF capability on a rover so that the CV will not have to contend with the hazards and complications involved with travel near the ocean surface.

Communications for status monitoring and asset redirection is also required at the task force level, so a communication capability is required between the CV and the rest of the task force. Asset redirection can typically be handled using low-bandwidth communications and the CV could be equipped with a low frequency long-range broadcast acoustic communications system for this task.

It would not be feasible to equip every vessel in the task force with a long-range system due to cost and size. Instead, an acoustic network could be established that would provide the communications link needed for vessel status reporting to the CV and for inter-vessel communications. Such a network could use shorter-range acoustic systems and employ specific vessels as network relay nodes. Interested readers are referred to the recent paper by Proakis et al. [3] on shallow water acoustic networks.

A communication rover can be used for infrequent high-rate communications such as sensor data transfer. As shown in Figure 1, the communication rover would travel to near the target vessel and establishes a high-bandwidth communication link using either high-frequency acoustics or optical systems.

C. POSITIONING

Positioning systems that use coupled Inertial Navigation Systems and Doppler Velocity Logs (INS/DVL) are available that can support long endurance operations with minimal position error. However, they are too costly and too large to deploy on all vessels and the DVL adds to an already difficult problem of acoustic interference between sensors. Furthermore, not all vessels require high precision positioning. Bathymetry survey vessels and obstacle detection rovers would require high-accuracy positioning, but a vessel collecting wave or sound velocity profile data would not. The communications rover would not require accurate positioning when transiting as it could seek on its target vessel using only a series of transponds for range. While it maintained station with respect to the target vessel, fairly accurate relative positioning would be required to avoid collision.

Figure 1 shows three potential schemes for a 'portable' task force positioning capability. The first utilizes a range-bearing approach with the CV equipped with a high quality INS/DVL positioning system and serving as the task forces' reference position. The CV would be equipped with a directional acoustic sensor that could be used to estimate the bearing of other UUVs in its vicinity. With this scheme a 'customer' vessel would initiate a transpond sequence with the CV that would include the customers' identification. The round trip travel time for this interaction provides the range between the two vessels, as is done with simple transponder systems. Shortly following the initial transpond, the CV would then provide the customer with its true bearing from the CV and the absolute position of the CV if required (note that for many scenarios only relative position with respect to the CV would be necessary).

A full 360° view directional acoustic sensor would be too large and cost-prohibitive to deploy on all vessels, and position accuracy degrades as a function of range from the CV due to a fixed angular resolution. A second potential scheme is to use range-range information from more than one vessel, and this would be useful for vessels that are too far from the CV to receive a bearing. This approach has the advantage that no special hardware is required as this can be accomplished strictly with acoustic communications. With this approach, a vessel would transpond to each of its neighbors in turn to obtain the range from itself to them. These ranges are then used to establish the vessel's relative position to its neighbors. If absolute position is necessary, then the initial transpond can be followed by a communication that provides the absolute position of each of the other vessels.

The third scheme is to use a 'Stationary' Rover that would act as a relocatable transponder. With this concept the rover could be very small and relatively inexpensive, equipped only with GPS, an acoustic modem and a rudimentary navigation package (magnetic compass). For this concept, rovers would swim to their assigned positions, surface for a GPS fix and then sink and moor to the bottom. Other vessels would then be able to use these rovers as a temporary long-baseline positioning system. When the task force moves into a new area, the rovers would reposition themselves under direction from the CV. A more sophisticated rover could deploy a bearing sensor package, and this concept has been advertised as a Navy Small Business Innovative Research Solicitation [4].

3. UUV TEAM CONCEPT FOR DEEP-WATER COMMERCIAL OPERATIONS

Military and commercial applications that would use multiple UUVs share the common problem of positioning and communications. While a commercial application typically has greater flexibility and could put a fixed infrastructure into place or use more ships, these approaches are not always economically desirable. This section illustrates two potential commercial scenarios that would use the positioning and communication schemes presented in the previous section to enable the cost-effective use of multiple UUVs.

A. SEAFLOOR SURVEY

Figure 2 illustrates how multiple UUVs could be used for seafloor surveying work that is commonly conducted in support of oil field exploration and cable or pipe route planning. The type of sensors that would be used for these types of operations would typically include bathymetry, acoustic imagery and sediment classification.

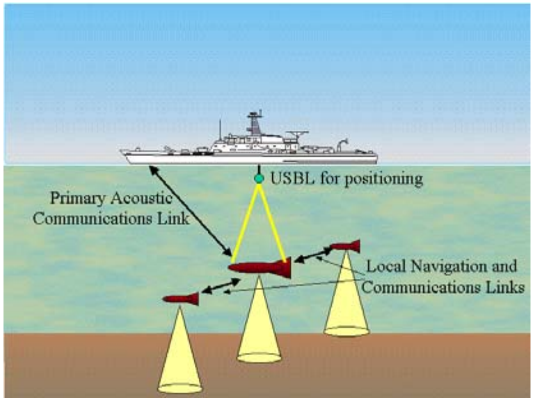

Figure 2. Multiple UUVs for a seafloor survey

This type of operation is already being conducted using a single UUV [1] and has been shown to be faster and cheaper than operations using a towed vessel for deep-water operations. The advantages of the UUV over the towed vessel include the ability to turn quickly and the elimination of the 2nd vessel that is required to be directly over the towed vessel for accurate positioning. For the UUV operation communications are conducted between the ship and the UUV using a dedicated vertical acoustic link, and vessel positioning is accomplished through a coupling of an INS/DVL on the vessel and an Ultra-Short Baseline (USBL) system on the ship.

Adding two more UUVs to this scenario would allow tripling of the coverage rate with the same ship. To employ the two extra vessels a few additional systems will be required. First, communications must be established between the ship and the two side vessels for control, status and data. This can be accomplished using the center vessel as a router and employing an independent communication system between the three vessels.

Since the position of the center vessel is known accurately, the positions of the side vessels could be determined using a short baseline system installed on the center vessel. The design of the short baseline system can be greatly simplified by establishing an operational requirement that the two side vessels follow the center vessel at pre-assigned relative positions. Finally, the two side vessels would need navigation algorithms for maneuvering to the center vessel and then for maintaining their assigned positions relative to the center vessel given their range and bearing from the center vessel.

B. SALVAGE OPERATION

ROVs are commonly used for a multitude of inspection tasks in oil field work, search and rescue and salvage operations. Because of their superior maneuverability, UUVs would be far more adept at this type of work and by using multiple UUVs the mission could be completed more quickly. One potential disadvantage of the UUV compared with the ROV is that acoustic communications may restrict the amount of sensor data that can be delivered to the operator in real-time. If this is the case, one option is to send portions of the data over the communications link and to record the full data on the vessel.

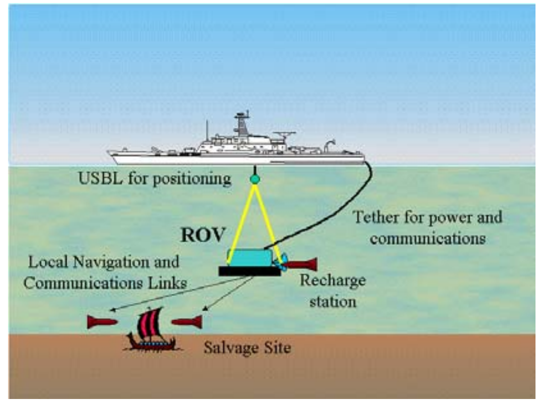

Figure 3. Notional salvage operation using multiple UUVs

Figure 3 shows a notional salvage operation employing multiple UUVs. In this scenario, the ROV serves as the Command Vessel at the operation site providing both positioning and communications for the UUVs. The power provided through the ROV's tether could be used to recharge the UUVs locally instead of sending them to the ship. As shown in the figure, the position of the ROV would be accurately determined using a USBL on the tending ship. The tether provides instantaneous high-bandwidth communications between the ship and the ROV.

For communications between the ship and the UUVs, the ROV would locate itself fairly close to the operation site so that high-bandwidth acoustic communications could be employed between the ROV and the UUVs. The ROV would act as a router between the UUVs and the ship. Given that the bandwidth of the acoustic communication system is high enough, it is possible that the UUVs could be remotely piloted from the ship. However, for this type of operation, it would likely be more desirable to utilize the available communication bandwidth for transmission of sensor data. As additional UUVs are added, the available bandwidth would have to be multiplexed between vessels, limiting the number of vessels that could be used in this scenario.

For positioning of the UUVs, the ROV would be equipped with its own USBL system that would be used to track the position of each UUV. This USBL system would need the capability to track multiple vessels simultaneously, by using a vessel ID as part of the transpond sequence. By putting the positioning burden on the ROV, the UUVs could use a very inexpensive positioning system consisting only of a magnetic compass.

4. MULTIPLE-UUV POSITIONING AND NAVIGATION RESEARCH AT NRL

The employment of multiple UUVs has the potential to provide new capabilities and also to lower the cost of operations presently conducted with ROVs. However, there are many technological challenges to be overcome to reach these goals. The focus of the research at NRL will be on the development of positioning and navigation schemes for multiple vessels that do not require a pre-deployed positioning and communication infrastructure.

A. VESSEL POSITIONING

Contending with the limitations of underwater communications is perhaps the single greatest challenge. When long-range, high-bandwidth and short-delay communications systems are feasible, developers have the option to use high-rate, long-range, precision positioning systems such as GPS. Underwater communications suffer from short-range, high-delay and low-bandwidth so long-range precise positioning systems are not viable. For the underwater application, vessel positioning requires an onboard self-contained system and/or the use of local short-range positioning approaches. Long-range systems are prohibitive for the scenarios considered due to their cost and size.

Acoustics is the only practical method for communicating any appreciable distance in the water, but the speed of sound in water results in significant propagation delays. The available acoustic spectrum that allows sufficient range with reasonably sized hardware for use on UUVs must also be shared with a variety of survey sensors. This problem is amplified further when multiple UUVs are operating in the same vicinity. It is thus prudent to minimize the communications bandwidth needed for vessel positioning and navigation tasks, and this is the emphasis in the planned research.

Another challenge that must be contended with for vessel positioning is the quality of sensors that are available for UUVs. High-accuracy low-drift positioning systems that do not require external frequent aiding from GPS or LBL systems are too large and costly for all but a few high-cost UUVs. Low-grade positioning systems, comprised of a magnetic compass and vessel speed based on propeller RPM can have position errors that grow on the order of meters or tens of meters a minute. The approaches that will be taken to overcome these issues in this research were illustrated in section 2. The primary approach that will be studied is the use of a single high cost vessel that will provide an accurate reference position for the task force. The other vessels in the task force will utilize low-grade positioning systems and determine their position relative to the reference position using a combination of range and bearing measurements to their neighbors.

B. VESSEL NAVIGATION

Vessel navigation is also significantly impacted by the underwater communication constraints. When long-range, high-bandwidth and short-delay communications systems are feasible, remote piloting of a vehicle (such as a radio-controlled aircraft) is possible. Normally, with the limitations of underwater communications, remote control of a UUV is not an option. Vessel navigation is a complex task and requires a significant level of machine intelligence to produce predictable behavior in the absence of human control.

The commercially available state of the art for single vessel autonomous navigation is essentially the ability to maneuver a vessel through a set of pre-planned waypoints with the assumption that no obstacles are in the way. Great strides are being made with land robots in this area, and robots are now on the market that can simultaneously generate a map of their surroundings and maneuver through an area without collisions.

Formation maneuvering, i.e. coordinated navigation of a group of vessels, has been predominantly the domain of humans; examples include naval ship task forces, combat aircraft and driving an automobile. In the examples cited, human intelligence is in the control loop and vision is the primary sensor. Even with this level of sophistication in intelligence and sensors, formation maneuvering can fail if a strict set of protocols is not employed. A good example of this is two cars driving in an open lot. Without the protocol of defined driving lanes and without knowledge of the other driver's intentions, this situation often results in confusion.

The approach that will be taken in this research will be first to determine and develop the low-level behaviors required to execute each step of a formation maneuver. These low-level behaviors will then be combined with an intelligent architecture that implements a strict protocol.

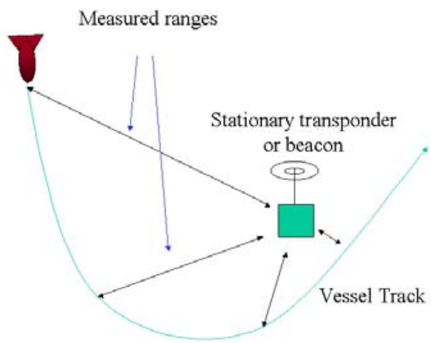

Figure 4. Range-only homing on a stationary transponder position

C. RESEARCH PLANS

The focus of this research will be on the development of approaches to inter-vessel relative navigation that use minimal hardware and minimal communication bandwidth. The position and velocity of surrounding vessels will have to be determined independently by each vessel by performing a series of maneuvers and doing a series of range and bearing measurements to the surrounding vessels. Sharing of position and velocity information between vessels will be allowed, but in many cases this will not be sufficient for successful navigation due to sensor errors. For example, a vessel may be told the velocity of the lead vessel, but if there is a 10-degree error in the heading sensor this information alone will not enable the vessel to follow the lead.

The first step in this research will be to develop the necessary low-level algorithms for simple tasks such as determining the position and velocity of other vessels using range only or a combination of range and bearing measurements. Determining the relative location of a fixed position, as shown in Figure 4, will require a series of maneuvers by a vessel that is equipped with a range-only sensor. Figures 5 through 7 show other positioning and navigation algorithms that will be needed by a vessel, such as obtaining and maintaining an assigned station relative to the lead vessel. An important part of this development step is the determination of achievable sensor characteristics that are needed to supply the information required to drive these algorithms. Sensor characteristics that need to be considered include range, range accuracy, bearing accuracy and bearing field of view.

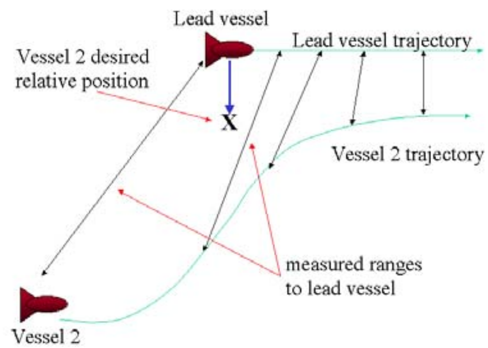

Figure 5. Intercept maneuver with another vessel

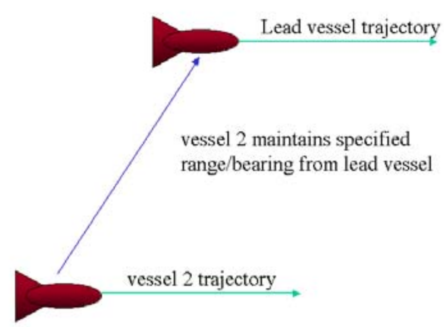

Figure 6. Vessel following maneuvering with range-bearing relative positioning

For autonomous operation of a vessel that is interacting with a group of other vessels, the vessel will need the ability to choose the proper low-level positioning and navigation algorithms that need to be executed given the current set of circumstances. This will require the development of an intelligent control architecture that will properly execute both the reactive and planned behaviors required. An initial approach to this type of architecture has been developed by the authors using subsumption [5].

A key issue that will be addressed in this research is the determination of the viability of the developed positioning approaches and navigation algorithms given the constraints on both communications and the accuracy of the proposed positioning sensors. We will need to examine the stability of vessel navigation and the accuracy of the estimated vessel positions given the parameters of sensor accuracy, update rates, number of vessels, range between the vessels, etc. This will be accomplished using computer simulations. For this task, a simulator will be developed that incorporates vessel inertia, sensor errors and communication restrictions including bit rate, delay, collisions and range. Finally, approaches that prove successful in simulation will be validated using land robots that will utilize only acoustics for sensing and communication.

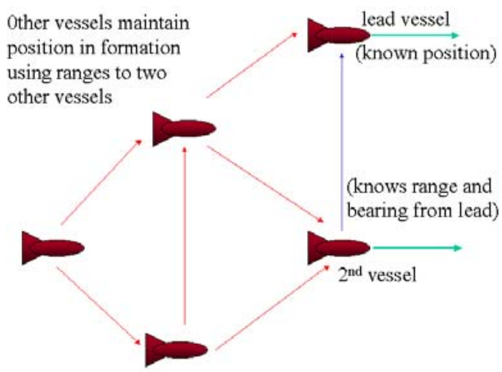

Figure 7. Vessel following maneuvering with range–range relative positioning.

5. SUMMARY

Underwater positioning without an extensive infrastructure and autonomous piloting of multiple vessels are outstanding research issues. Teams of UUVs are needed to accomplish military near-shore missions and can also be used to improve the cost effectiveness of commercial operations. The UUV team navigation and positioning approaches being developed by NRL will be applicable to both endeavors.

ACKNOWLEDGEMENTS

This work was funded by the Office of Naval Research through the Naval Research Laboratory under Program Element 62782N. The mention of commercial products or the use of company names does not in any way imply endorsement by the U.S. Navy. Approved for public release; distribution is unlimited. NRL contribution number NRL/PP/7440-01-1015.

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